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A STUDY OF THE COMBUSTION OF ALUMINUM BOROHYDRIDE

IN A SMALL SUPERSONIC WIND TUNNEL

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SUMMARY

The combustion of aluminum borohydride in the Mach 2 airstream of a 3.84- by 10-inch wind tunnel was studied by analyzing gas samples taken from the airstream. Gas mixture composition was determined with the aid of a vacuum apparatus and gas chromatograph. The overall combustion efficiency of the fuel was assumed to be good because the combustion efficiency of its hydrogen component was found to be high. The increase of the lateral surface area of the combustion region was dependent upon the degree of mixing of fuel and its combustion products with air. In the flame zone where there was insufficient oxygen for complete combustion, the metal components of the fuel appeared to burn preferentially to the hydrogen component.

INTRODUCTION

The work presented in this paper was part of a general research program on combustion in supersonic airstreams that was conducted at the NASA Lewis Research Center. Previous papers have dealt with the problem of establishing combustion (refs. 1 to 3) and with aerodynamic effects (refs. 4 to 8). The object of this study was to elucidate some of the details of the mixing and combustion processes.

The experiments were conducted in the Mach 2 airstream of a 3.84- by 10-inch wind tunnel. After a flame was established by burning aluminum borohydride, samples of combustion gases were taken from the flame zone through holes in the top wall of the tunnel. These samples were subsequently analyzed with the aid of a vacuum apparatus and gas chromatograph.

APPARATUS AND PROCEDURE

The 3.84- by 10-inch Mach 2 wind tunnel and the techniques used to establish combustion have been thoroughly described in reference 3. Gas samples were taken through pressure-tap holes located flush with the top tunnel wall. Evacuated glass bottles were attached to the pressure taps, and the bottles were opened shortly after the flame appeared. A few seconds later, while the flame was still present, the sample bottles were closed. In six runs the bottles were closed a fraction of a second after the flame had disappeared. The differences in the data from these two methods of sampling were well within experimental error, and hence the data were combined. Subsequently, the bottles were removed from the tunnel and the gas samples were analyzed to determine the volume percent (mole fraction) of H_2O, O_2, N_2, and H_2 present. No attempt was made to analyze any solid products collected along with the gaseous samples.

In the analytical procedure, each sample bottle was first attached to a vacuum apparatus. Then the pressure, volume, and temperature of the sample were measured, and the total amount of gas present was calculated. The water vapor was separated by passing the gas mixture through a -196° C cold trap. The pressure and volume of this water were subsequently measured, and the percent H_2O in the gas sample was thus determined. The other noncondensible gases O_2, N_2, and H_2 were removed from the vacuum apparatus with a Töpler pump. Finally, this gas mixture was analyzed for percent H_2, O_2, and N_2 with a gas chromatograph (ref. 9).

RESULTS AND DISCUSSION

Since figure 1, which is an actual photograph of the combustion of aluminum borohydride in the Mach 2 wind tunnel, does not show very much detail, figure 2 is presented as a better illustration of this phenomenon. It is an interpretation of information gathered from previous experiments and shows how the fuel flowing from the top tunnel wall penetrates to about 1/4 inch into the supersonic airstream before it is appreciably atomized and mixed with air. The main airstream adjacent to the top tunnel wall separates just ahead of the point of fuel injection, skirts the fuel jet, and recombines just behind the jet. Downstream from this point the fuel and air form a homogeneous burning mixture. Thus, there is a small pocket of nearly pure air adjacent to the tunnel wall just behind the point of fuel injection.

Figure 3 summarizes the results of the analyses of 132 gas samples taken at various positions along the top tunnel wall. The data are from a total of ten runs. The data at each tunnel position varied over a wide range of values from run to run, especially in the flame zone. Therefore, the average values are plotted, and the curves are drawn through them.

The vertical lines show the maximum scatter about the average value. The curves show that, in the flame zone (taps 5 to 12), there is a high percentage of hydrogen present with almost no water. Farther downstream in the heated region (taps 13 to 18), the gas composition is that of air with a slight amount of water present. Thus, the overall combustion efficiency seems to be high by the time the gases reach the heated region. The presence of the pocket of air depicted in figure 2 is evident in figure 3 (near tap 6) as well as in some of the later figures.

Examination of figure 3 shows that in the flame zone the percentage oxygen is low while the percentage hydrogen is high. Farther downstream the percentage oxygen is high and the hydrogen has burned to form water. This observation indicates that, as the aluminum borohydride burns, the metal components (aluminum and boron) are oxidized first, followed by the hydrogen. This behavior has been observed by other investigators (refs. 10 and 11). One reason proposed for the large amount of hydrogen found in the borohydride flame zone is that any water that may have formed in the flame zone continues to react with aluminum borohydride or intermediates to form additional hydrogen. This water reactivity distinguishes the combustion of borohydrides from most other fuels such as hydrocarbons, in that one of the final products of combustion can rapidly react with the starting material.

From the average values of percent composition and the stoichiometry for the combustion of aluminum borohydride in air, equations can be derived (appendix) for determining the mixing ratio θ, defined as the ratio of the concentration of gaseous combustion products H_2 and H_2O to the concentration of N_2. This parameter is plotted against position along the tunnel wall in figure 4. The mixing ratio θ decreases uniformly after it reaches its maximum value at tap 8.

In figure 3 the gas composition downstream of the flame zone was found to be almost pure air with a small amount of water present. This observation and the observation from figure 4, that θ continuously approaches zero downstream from the flame zone, show that the combustion products from the flame zone are being continuously diluted by mixing with more air from the main airstream and undergoing further combustion. As shown in the appendix, θ is indirectly the volumetric fuel-air ratio. Therefore, the curve of figure 4 is a measure of the degree of mixing of fuel or its combustion products with air or N_2 at the various positions along the tunnel wall. The θ curve, being only a measure of the degree of mixing, would not in itself describe the mixing phenomenon. The mixing process would also depend largely upon the geometry of the combustion zone, particularly upon the lateral surface area of the flame front.

This relation may be tested as follows: Since θ indirectly represents the ratio of the volume of fuel to the volume of air, and the quantity of fuel (or its combustion products) is constant at all tunnel positions, the decrease in θ with distance downstream of the point of fuel injection must be the result of influx of air into the combustion zone from the main airstream. As the combustion zone grows larger, more air flows into it. Consequently, it is reasonable to expect that the flow of air into this region should be proportional to the changing lateral surface area A of the combustion zone, going downstream from the point of fuel injection. Therefore,

$$\theta \propto \frac{1}{A}$$

A plot of θ against $1/A$ is shown in figure 5. The geometric shape of the combustion zone is assumed to be half of a cone, as deduced from figure 1. The data seem to fall on a straight line, indicating that the decay of θ with distance downstream of the injector is attributable to simple mixing of the fuel or its combustion products with air.
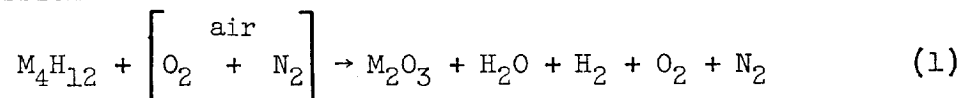
CONCLUSIONS

A study of the combustion of aluminum borohydride in a supersonic wind tunnel by analyzing gas samples taken from various stations along the top tunnel wall produced the following conclusions:

1. The metal components of the fuel appear to react preferentially with the air until there has been sufficient mixing so that there is enough air to burn the hydrogen.

2. Although the fate of the metal components of the fuel is unknown, the overall combustion efficiency seems high because the unburned hydrogen found in the flame zone had completely burned to form water by the time it reached the end of the heated zone.

3. The increase of the lateral surface area of the combustion region was found to be dependent upon the degree of mixing of fuel and its combustion products with air.

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APPENDIX - DERIVATION OF MIXING RATIO θ

The combustion of aluminum borohydride $Al(BH_4)_3$ (or expressed in terms of metal and hydrogen, M_4H_{12}) in air can be described by the following expression:

$$M_4H_{12} + \left[\begin{array}{ccc} & \text{air} & \\ O_2 & + & N_2 \end{array} \right] \rightarrow M_2O_3 + H_2O + H_2 + O_2 + N_2 \tag{1}$$

In the gaseous analytical procedure used in this combustion study, no attempt was made to analyze for the metal components of the fuel; therefore, the following equation can be written for the combustion of the hydrogen component of the fuel with air:
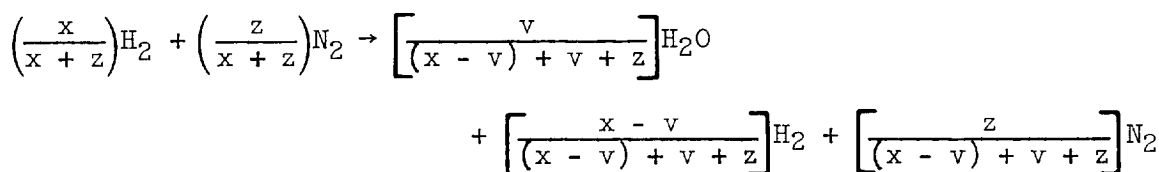
$$xH_2 + yO_2 + zN_2 \rightarrow vH_2O + (x - v)H_2 + (y - \frac{v}{2})O_2 + zN_2 \tag{2}$$
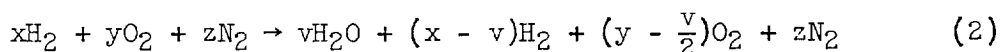
where coefficients x, y, z, v, $(x - v)$, and $(y - \frac{v}{2})$ represent the number of moles of reactants and products.

The mixing process prevailing in this combustion study can be described by the ratio of the concentration of hydrogen to air. Consequently, either side of equation (2) can be used to describe the mixing process, if the concentration of hydrogen expressed in the ratio is the total concentration of hydrogen regardless of its chemical form. Since the oxygen in the air is continuously combining with hydrogen (or with metal to form metal oxides), the nitrogen must be considered in the mixing process as the agent that is diluting the total hydrogen.
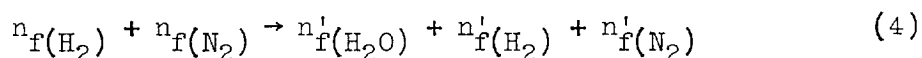
Thus, equation (2) can be rewritten considering only the terms involved in the mixing process:

$$xH_2 + zN_2 \rightarrow vH_2O + (x - v)H_2 + zN_2 \tag{3}$$
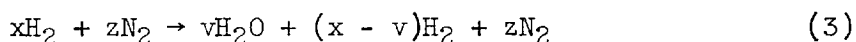
or, expressing it in terms of mole fraction of reactants and products respectively, it is

$$\left(\frac{x}{x + z}\right)H_2 + \left(\frac{z}{x + z}\right)N_2 \rightarrow \left[\frac{v}{(x - v) + v + z}\right]H_2O$$

$$+ \left[\frac{x - v}{(x - v) + v + z}\right]H_2 + \left[\frac{z}{(x - v) + v + z}\right]N_2$$

or

$$n_{f(H_2)} + n_{f(N_2)} \rightarrow n'_{f(H_2O)} + n'_{f(H_2)} + n'_{f(N_2)} \tag{4}$$

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where n_f is the mole fraction or volume percent of the various constituents.

Therefore, the θ curve of figure 4 is calculated from the following equation:

$$\theta = \left[\frac{n_f(H_2)}{n_f(N_2)} \right]_{reactants} = \left[\frac{n_f'(H_2O) + n_f'(H_2)}{n_f'(N_2)} \right]_{products} \tag{5}$$

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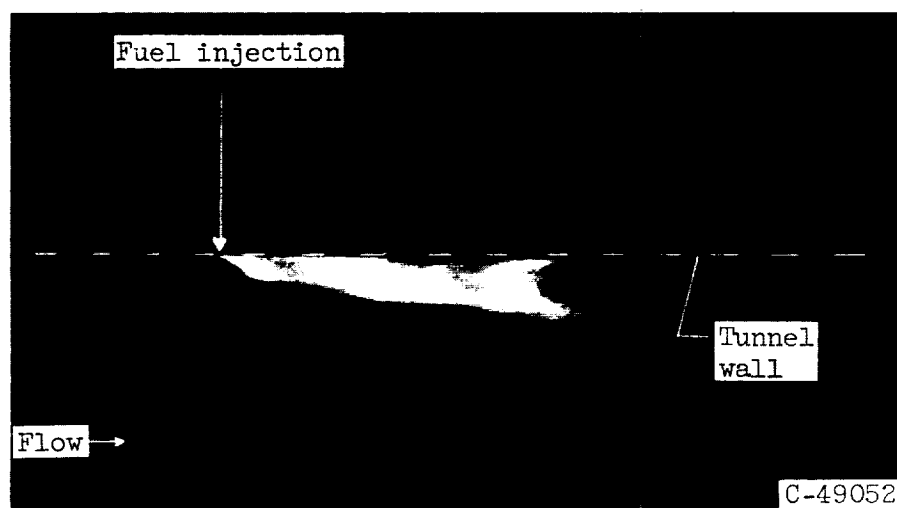11. Parker, W. G., and Wolfhard, H. G.: Properties of Diborane Flames. Fuel, vol. 35, 1956, pp. 323-332.

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Figure 1. - Direct photograph of the combustion of aluminum
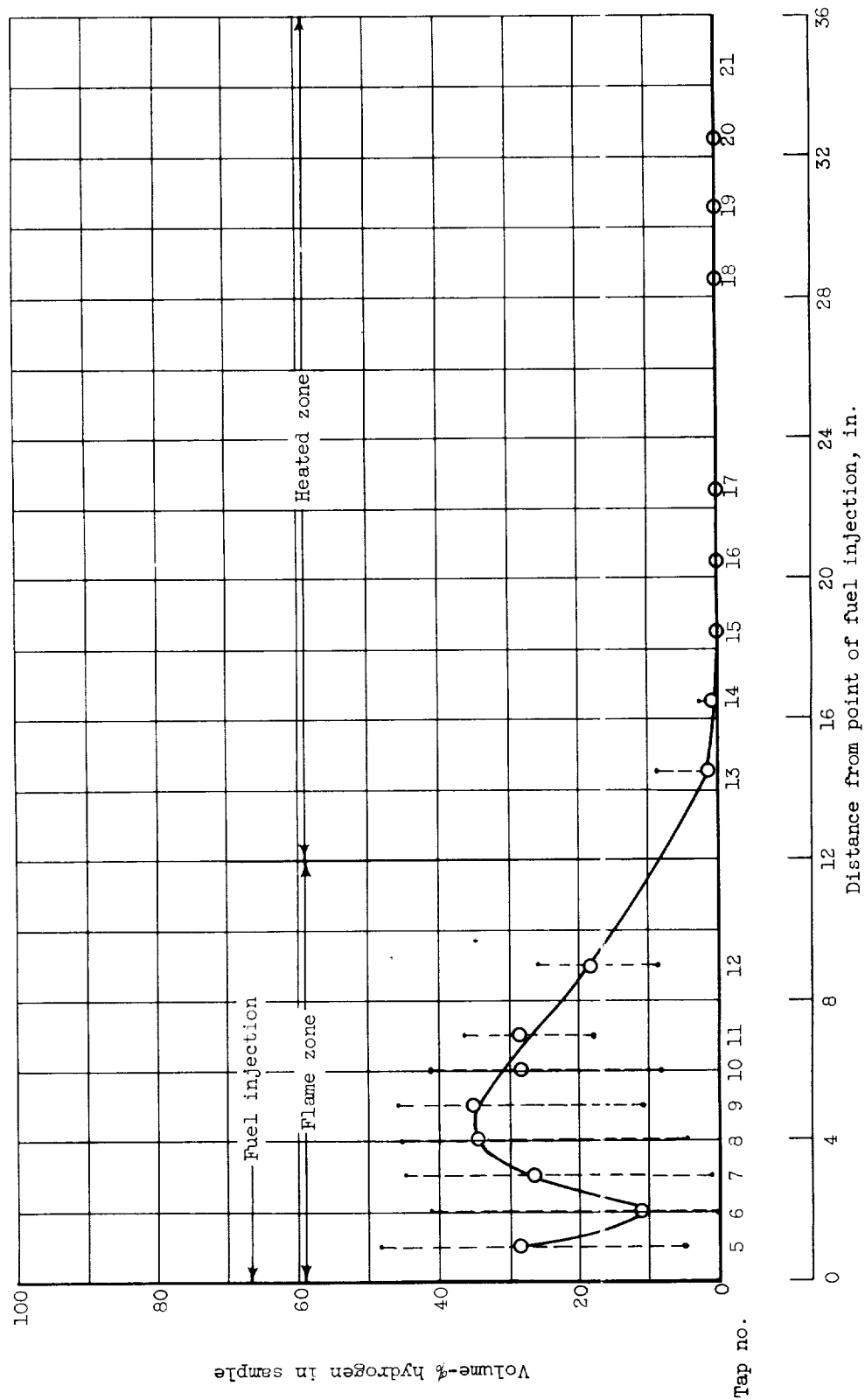borohydride in the Mach 2 wind tunnel.
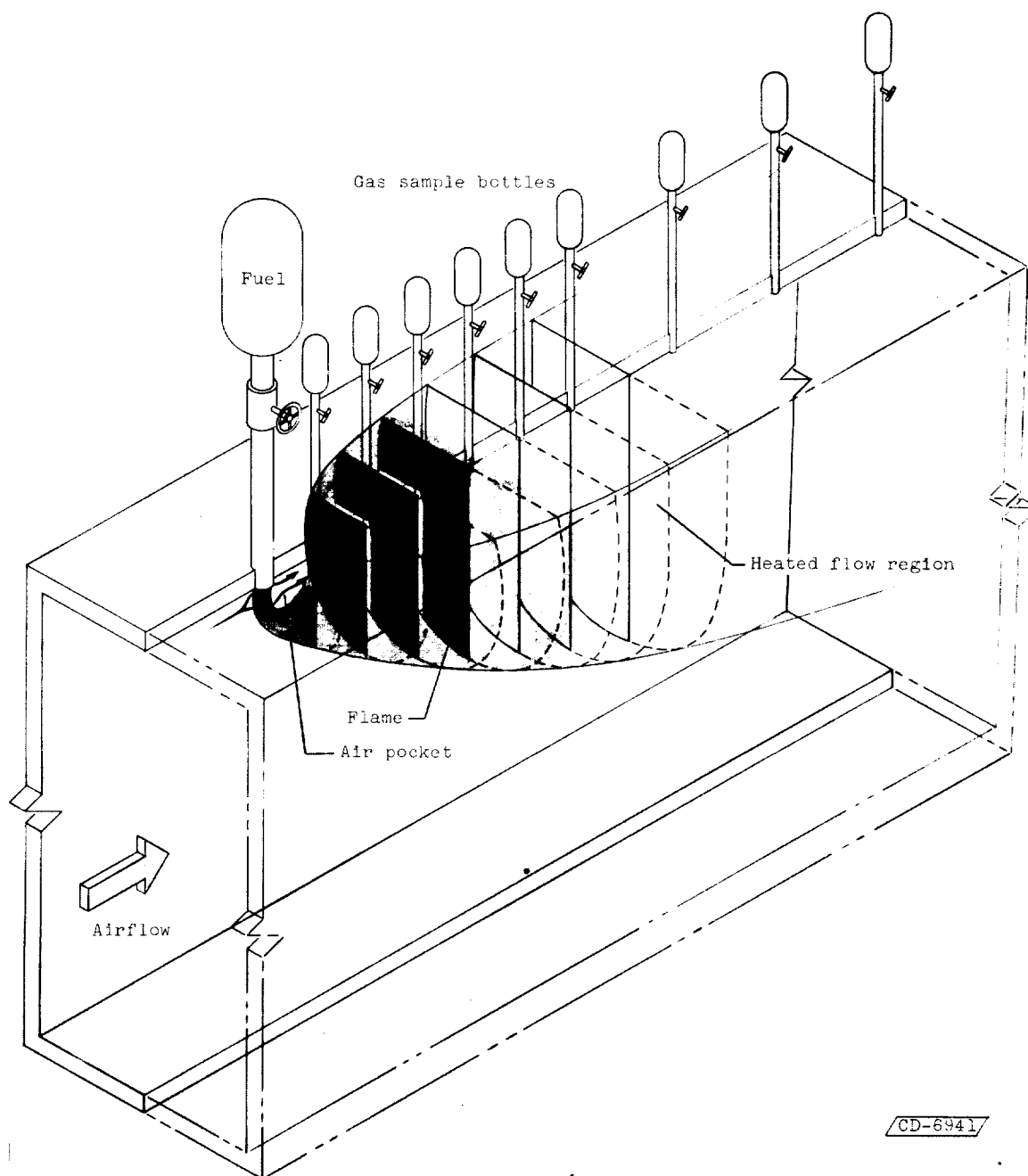
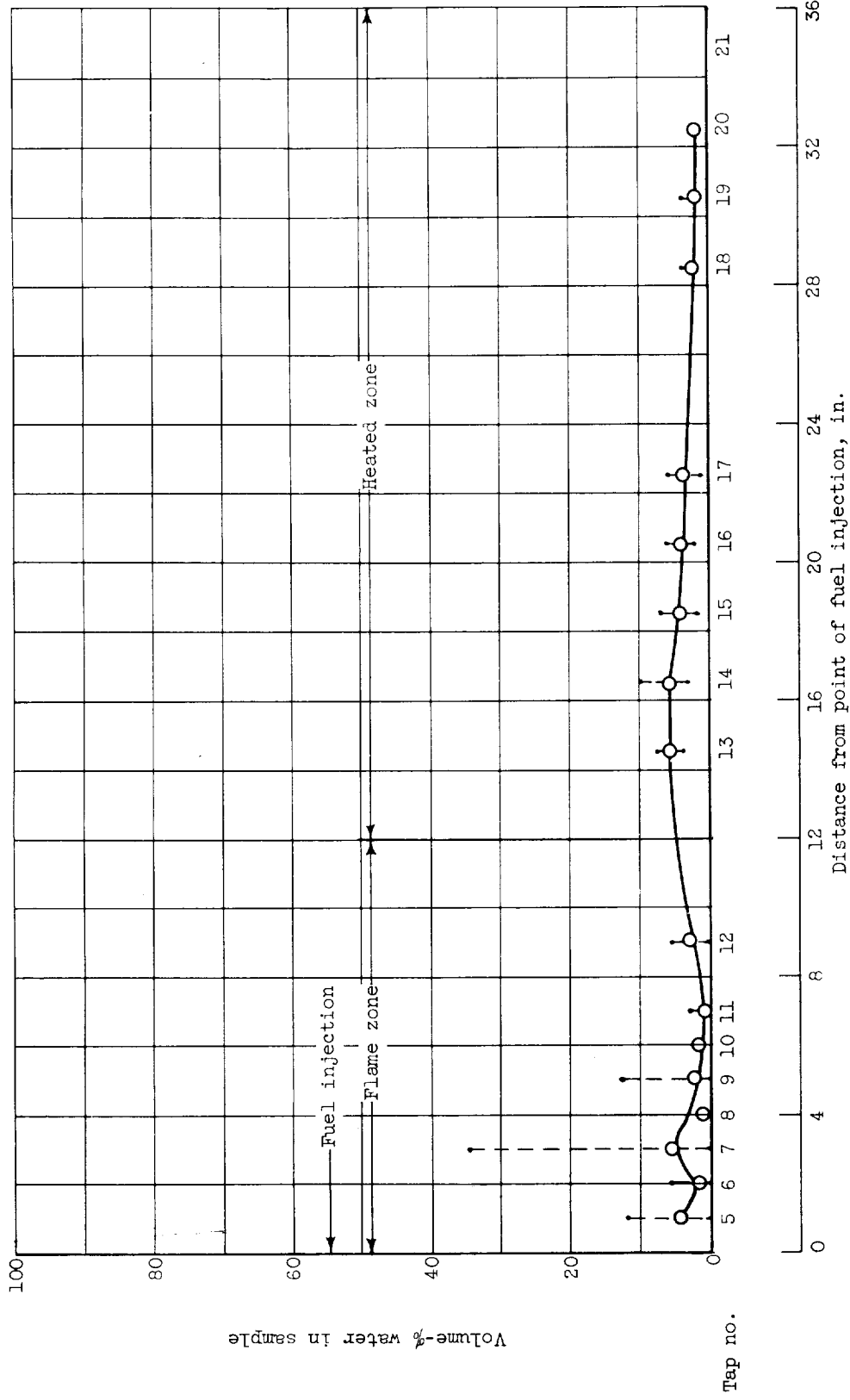Figure 2. - Diagrammatic sketch of combustion of aluminum borohydride in Mach 2 wind tunnel.

Figure 3. - Gas-sample analysis at each of various positions along top tunnel wall.

(a) Hydrogen analysis.

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(b) Water analysis.

Figure 3. - Continued. Gas-sample analysis at each of various positions along top tunnel wall.
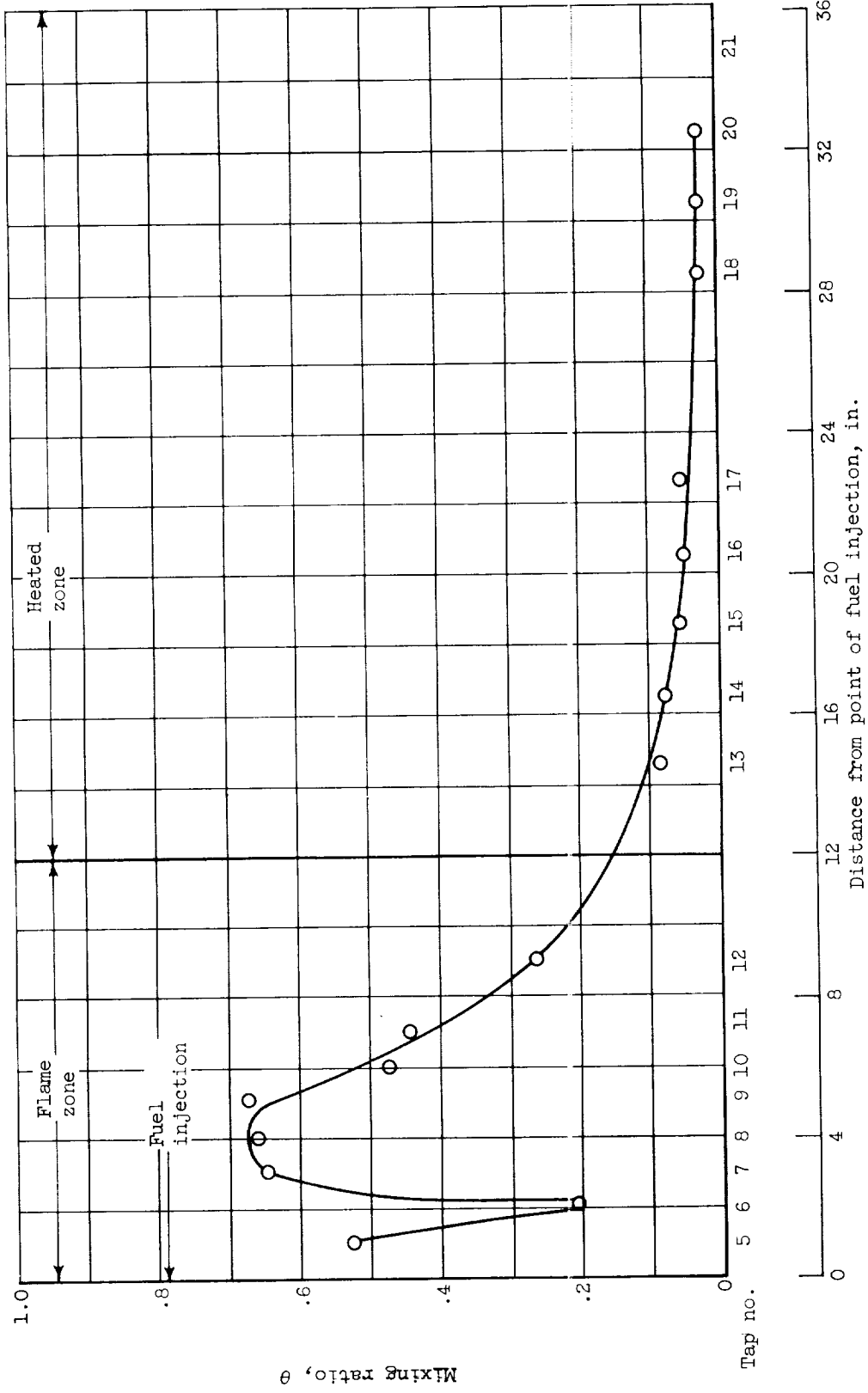
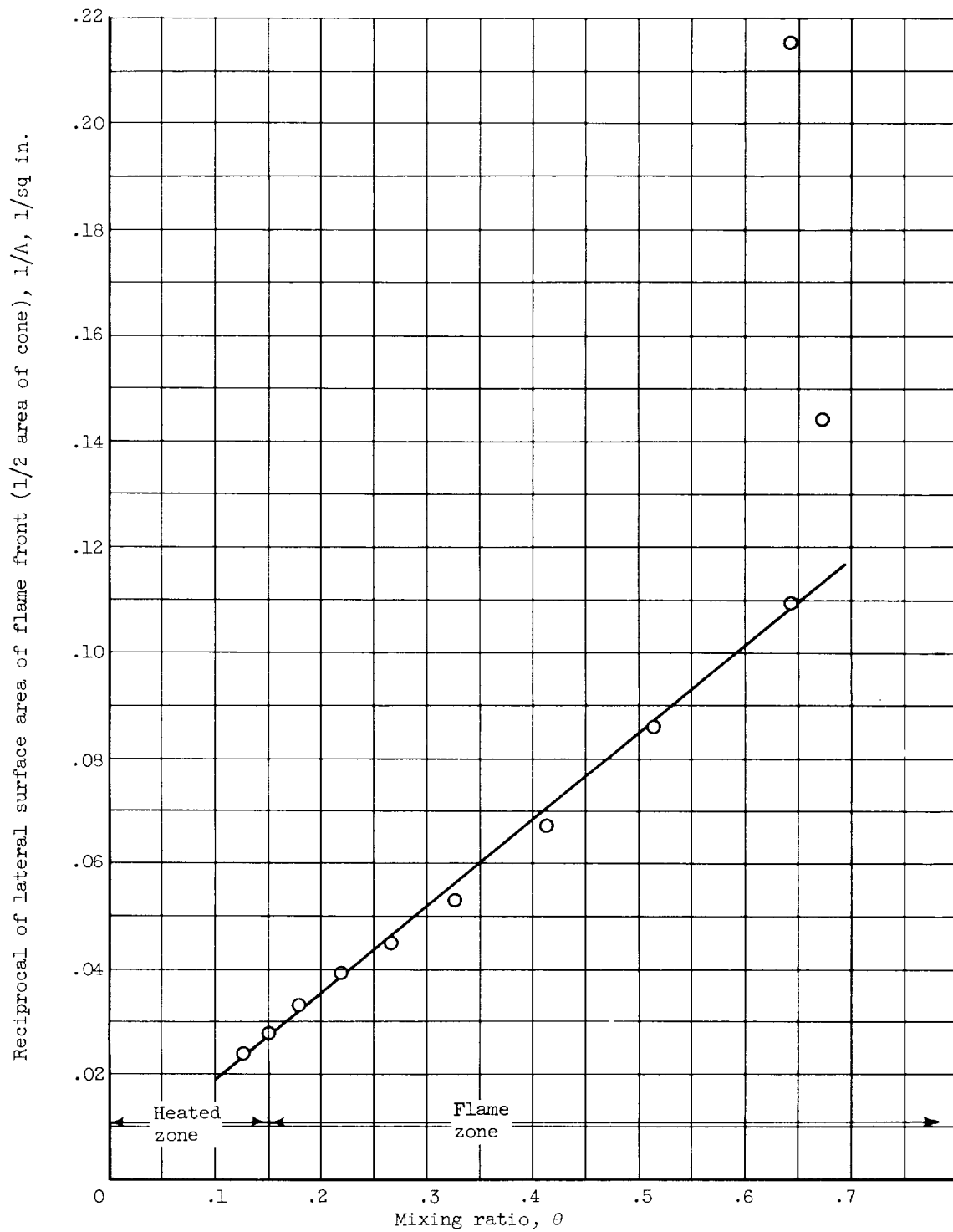Figure 4. - Mixing-ratio distribution along top tunnel wall.

Figure 5. - Relation between mixing ratio and lateral surface area of flame front.